The NPDGamma Experiment

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The nature of weak interactions between strongly interacting hadrons is not well understood. The NPDGamma ($\vec{n} + p \rightarrow d + \gamma$) experiment,[1] currently under construction at the LANSCE, will study the parity-violating weak interaction between the most common hadrons, protons, and neutrons. The hadronic weak interaction is observed in nuclei and nuclear processes,[2] but interpretation of these experiments is difficult because of the complicated many-body dynamics of a nucleus. The goal of the NPDGamma experiment is to measure the parity-violating directional gamma-ray asymmetry in the reaction $\vec{n} + p \rightarrow d + \gamma$ to an accuracy of 5×10^{-9}, which is approximately 10% of its predicted value.[3,4] Such a result, in a simple system, will provide a theoretically clean measurement of the weak pion-nucleon coupling, thus resolving the long-standing nuclear-physics controversy over its value.

Theory Background

The flavor-conserving weak interaction between hadrons is the most poorly tested aspect of electroweak theory.[4] While much is known about quark-quark weak interactions at high energies, the low-energy weak interactions of hadrons (particles made of quarks, such as the nucleons—the proton and the neutron) are not well measured. At low energies, the effects of the weak interaction are typically obscured by other processes, making their experimental study challenging. In terms of the meson-exchange picture of the weak nucleon-nucleon interaction,[4] the weak-pion exchange is particularly interesting because it is the longest-range component of the interaction and is therefore presumably the most reliably calculable. The hadronic exchange of neutral currents, which is expected to dominate the weak-pion exchange between nucleons, has not been isolated experimentally in an unambiguous way. For both of these reasons, the coupling constant, H_π^1, for pion exchange in the weak nucleon-nucleon interaction is of special interest.

An accurate measurement of H_π^1 in a simple nucleon-nucleon system is needed to resolve previous experimental inconsistencies. A two-nucleon system, such as in the $\vec{n} + p \rightarrow d + \gamma$ process, is sufficiently simple that the measured asymmetry of the emitted gamma rays can be related to the weak meson-nucleon-nucleon coupling with negligible uncertainty to nuclear structure. The relationship between the parity-violating asymmetry A_γ and H_π^1 (where A_γ is the correlation between the direction of emission of the gamma ray and the neutron polarization) is calculated to be $A_\gamma \approx -0.045\ H_\pi^1$. The goal of NPDGamma is to measure A_γ to a precision of $\pm 5 \times 10^{-9}$, which will determine H_π^1 to $\pm 1 \times 10^{-7}$. Such a result will clearly distinguish between the values for H_π^1 extracted from experiments in nuclear systems and between predictions by various theories of the weak interaction of hadrons in the nonperturbative QCD regime.

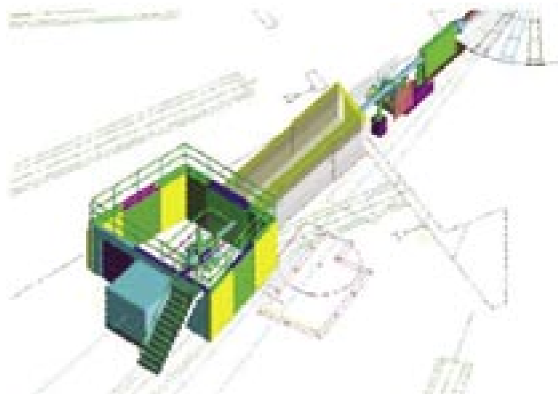

Figure 1. Depiction of FP12 at the Lujan Center at LANSCE. Construction of the flight path and the experimental cave is essentially complete. Commissioning of the flight path and the experimental apparatus will begin in January 2004.

NPDGamma Experiment

To determine H_π^1 with an uncertainty of 1×10^{-7}, we must achieve a statistical uncertainty of 0.5×10^{-8} on A_γ. This means that the experiment must detect a few $\times 10^{17}$ of the 2.2-MeV gamma-rays from the $\vec{n} + p \rightarrow d + \gamma$ reaction. In addition, possible systematic errors in the experiment require careful attention. The tiny parity-violating signal in the reaction will be isolated by flipping the neutron spin. The real asymmetry will change sign under spin reversal, while spin-independent false asymmetries will not. The weak interaction is the only fundamental-particle interaction that can produce a parity-violating signal; parity violation is simply described as a difference between a physical process and its mirror image. For example, in the $\vec{n} + p \rightarrow d + \gamma$ reaction, if more gamma rays are emitted in the same direction as the neutron spin, rather than in the opposite direction, then that is a parity-violating signal and must be caused by the weak interaction. The experiment then consists of observing the direction of emission of the gamma rays from many $\vec{n} + p \rightarrow d + \gamma$ captures, and if there is an asymmetry in their distribution with respect to the neutron-polarization direction, the effect of H_π^1 has been observed.

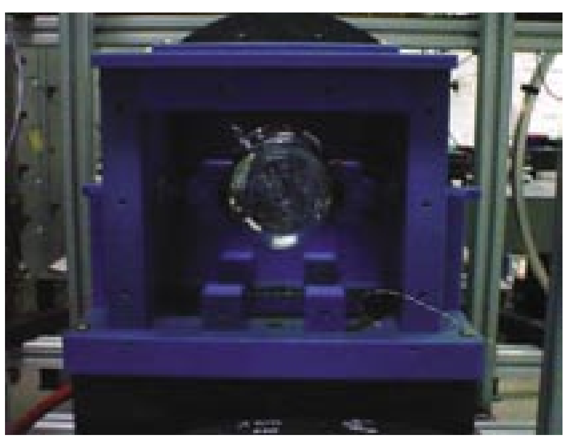

Figure 2. The ^{3}He spin filter used to polarize the neutron beam. The glass cell is 11 cm in diameter and contains ^{3}He and rubidium. A laser is used to polarize the rubidium atoms, which then transfer their polarization to the ^{3}He nuclei. The blue structure is used to support the glass cell and to provide an environment where it can be kept at a warm temperature (150°C) to produce rubidium vapor.

The requirements for the experiment are a large number of polarized, cold neutrons; a method of flipping the neutron polarization; a proton target; and a detector system for the 2.2-MeV gamma rays. The experiment consists of a pulsed, cold neutron beam, transversely polarized by transmission through polarized ^{3}He, with polarization reversal achieved on a pulse-by-pulse basis by an rf spin flipper. The neutrons are incident on a liquid parahydrogen target. The 2.2-MeV gamma rays from the capture reaction will be detected by an array of cesium-iodide scintillators coupled to vacuum photodiodes and operated in current mode.

Cold Neutron Beam and Polarizer

The experiment requires a high flux of cold neutrons with energies below 15 meV. Although such neutrons are available from cold moderators at both reactors and spallation neutron sources, the nature of the neutron flux from a pulsed spallation source provides a very powerful diagnostic tool for a number of possible systematic effects for this experiment. At LANSCE, the cold neutron source consists of a liquid-hydrogen moderator coupled to the 20-Hz pulsed neutron source. At cold-neutron energies, it is possible to use neutron guides to transport neutrons. Just as a difference in the indices of refraction will cause total internal reflection of light incident at shallow angles on the interface between two media, magnetic properties of the surface of a neutron guide can be used to reflect neutrons incident at glancing angles (below a well-known critical angle) on the guide surface. The function of the neutron guide is to conserve the high cold-neutron flux available near the moderator.

For the experiment, a new beam line and neutron guide, flight path 12 (FP12), have been built at the Lujan Center.[5] A drawing of the FP12 layout with the experimental cave at its end is shown in Figure 1. To observe parity violation (in the distribution of gamma rays with respect to the neutron-polarization direction), the experiment requires polarized neutrons. Cold neutron beams can be polarized in several ways, but the best technology for NPDGamma is a ^{3}He spin filter.[6] ^{3}He spin filters (Figure 2) are compact, possess a large phase-space acceptance, produce a negligible fraction of capture gamma-ray background, and do not require strong magnetic fields or produce field gradients. This is important for the control of systematic errors in the experiment. The thickness of the spin filter can be optimized for polarization versus transmission.

Neutron Spin Flipper

For NPDGamma, the neutron spins are flipped on a 20-Hz pulse-by-pulse basis with an rf spin rotator, or spin flipper (RFSF). The RFSF is a shielded solenoid that operates according to the well-known principles of nuclear magnetic resonance. In the presence of a homogeneous constant magnetic field and an oscillating magnetic field in a perpendicular direction, the neutron spin will precess, and the amplitude of the oscillating field can be selected to precess the spin by 180° as the neutron travels through the spin-flipper volume. The spin flip is introduced on a pulse-by-pulse basis by simply turning the rf field on and off. The solenoid produces only negligible external magnetic fields and field gradients—an important property given the possible sensitivity of the detector apparatus to magnetic-field-induced gain shifts.

Proton Target

In the liquid-hydrogen (proton) target, it is essential that the polarized neutrons retain their polarization until they are captured. Many of the neutrons will scatter in the target before they are captured, and the spin dependence of the scattering is therefore important. The ground state of the hydrogen molecule (known as parahydrogen) has spin of zero (J=L=S=0), and the first excited state, the lowest orthohydrogen state, is at 15 meV above the parastate. A large fraction of the cold neutrons possess energies lower than 15 meV. Because these neutrons cannot excite the parahydrogen molecule into its first excited state, only elastic scattering and capture are allowed, and spin-flip scattering is forbidden. The neutron polarization therefore survives the scattering events that occur before the capture. Higher-energy neutrons will undergo spin-flip scattering and therefore lose their polarization. The liquid-hydrogen target must be in the parastate. For liquid hydrogen held at 20 K and atmospheric pressure, the equilibrium concentration of parahydrogen is 99.8%, which is low enough to ensure a negligible population of orthohydrogen.

Figure 3. The gamma-ray detector array includes 48 cesium-iodide crystals. The housings of 16 of the crystals are visible in the photo. The effect of the hadronic weak interaction is measured as an asymmetry in the event rate between the upper and lower detector hemispheres. The RFSF is mounted on the left side of the array.

Cesium-Iodide Gamma-Ray Detector Array

Finally, the experiment must detect the 2.2-MeV gamma rays from the neutron capture. Given the small size of the expected asymmetry and the goal precision of the experiment, the number of events required to achieve sufficient statistical accuracy in a reasonable time immediately leads to the conclusion that the 2.2-MeV gamma rays must be counted in current mode. This means that instead of observing individual events in the detector, many are seen at once, and the sum of their presence is detected as a total voltage or current from the detector electronics rather than as individual pulses. It is important to demonstrate in a current-mode measurement that the electronic noise is negligible compared to the shot noise because of

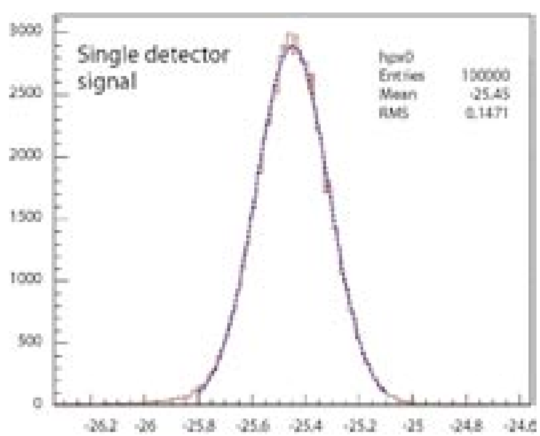

Figure 4. A histogram of a detector signal, measuring the electronic noise. The width of the distribution is of order 0.1 mV, which corresponds to the theoretical limit due to preamplifier Johnson noise of 20 fA/√Hz . This will allow the current-mode detectors to take data at the counting-statistics limit and to quickly demonstrate that no false asymmetry effects are observed in the electronics and data-acquisition system.

the discrete nature of the energy deposited by each gamma ray and the number of photoelectrons produced by each event. In addition, the detector must cover a large solid angle with a large, time-independent efficiency that is unaffected by neutron spin reversal and radiation damage. Segmentation of the detector is required to resolve the angular dependence of the expected parity-violating signal and to discriminate false effects. A photo of the fully constructed detector array of 48 cesium-iodide scintillator crystals is shown in Figure 3. The noise performance of the detectors and their preamplifier electronics has been measured in the laboratory, and it corresponds well to predictions based on the fundamental limit of Johnson noise. (A histogram of a single detector signal is shown in Figure 4, and the width of the distribution is a measure of the noise in the electronics.) This will allow the detectors to accumulate data at the counting statistics limit and to quickly demonstrate that no false experimental effects exist in the electronics.

Conclusion

A sensitive measurement of the parity-violating gamma asymmetry in the reaction $\vec{n} + p \rightarrow d + \gamma$ can give definitive information on one of the most important and interesting components of the weak nucleon-nucleon interaction. Engineering runs have demonstrated the performance of the essential components of the experiment; this includes published results for the FP12 moderator performance and measurements of parity-violating asymmetries in neutron capture on nuclear targets (chlorine, cadmium, and lanthanum) to a precision of 6×10^{-6}—limited only by counting statistics. Construction of the detector array is complete and laboratory tests indicate that noise levels of the electronics are close to the theoretical limits and thus allow the measurement of asymmetries at the level of a few parts per billion. The experimental design incorporates a number of powerful diagnostics to isolate systematic effects. Commissioning of the final construction of the experiment will begin in early 2004, and data taking will commence in late 2004. The NPDGamma experiment to search for the parity-violating gamma asymmetry in the reaction $\vec{n} + p \rightarrow d + \gamma$ will achieve a sensitivity that is likely to obtain a nonzero result, providing an experimental and unambiguous measure of the hadronic weak interaction in a simple and calculable system.

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Acknowledgment

Assistance in the construction and design of this experiment has been provided by LANSCE-12 and LANSCE-3. This work was supported in part by the DOE Office of Energy Research (Contract W-7405-ENG-36), the National Science Foundation (Grant No. PHY-0100348), and the Natural Sciences and Engineering Research Council of Canada.

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